Beam-beam phenomena in the Tevatron
Status Report

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1 Introduction

At the start of Run II, transfer efficiencies in the Tevatron were severely limited by beam-beam effects. The major losses were those of anti-protons during the squeeze. Smaller but significant anti-proton losses also ocurred at 150 GeV and during acceleration. Most of these losses have been overcome by changing the helices to increase the beam separations, with smaller anti-proton emittances and by operating at lower chromaticities. The average transfer efficiencies from injection to low-beta in the Tevatron were 89% and 93% for protons and anti-protons respectively in January 2004. There is some room for improvement, especially during the acceleration. As beam intensities increase, it is possible that beam-beam related losses will increase without further improvements. If the losses and emittance growth can be controlled at design beam intensities, then it may be possible to attain higher luminosities with beam currents larger than design values.

Head-on beam-beam interactions are often characterized by a single parameter - the head-on beam-beam tune shift. This is the tune shift of a small transverse amplitude particle and it is also a measure of the beam-beam induced tune spread in the bunch. These head-on interactions drive only even order resonances so the tunes in colliders are chosen such that the tune footprint does not straddle low even order resonances below the twelfth. While much is understood about head-on interactions, several phenomena lack quantitative predictions, e.g. emittance growth with mismatched beams.

Long-range interactions are more complex than the head-on interactions. In addition to changing the tunes, these interactions in general also change the orbits, coupling and chromaticity. As with the tune changes, the orbit, coupling and chromaticity changes are amplitude dependent. The long-range interactions drive both even and odd order resonances. The changes in orbits, tunes, coupling, chromaticity, resonance strengths depend on several parameters including: beam separations, plane of the helix, beam emittance, beta functions, dispersion, phase advances between the interactions etc. If for example, the phase advances between the parasitics can be adjusted with independently powered quadrupoles as is done in CESR, then the resonance strengths can be significantly altered. Quadrupoles in the Tevatron are on the same bus as the main dipoles, thus ruling out that option. Instead the most direct way of minimizing the impact of the long-range interactions in the Tevatron is by manipulating the helix configuration and with lower beam emittances.

While it is tempting to ask for a single figure of merit that captures the impact of the long-range interactions, it is unlikely that such a parameter exists given the complexity of the effects. Here we list a select number of parameters that are important and that can be controlled:

- Smoothness of the helix (too small or too large beam separations should be avoided).
- Small beam emittances
- Low machine chromaticity
- Proper choice of machine tunes
- Low machine coupling

2 Theoretical studies

A first step is understanding how quantities like tune shifts, coupling, chromaticity, resonance strengths depend on beam parameters. These calculations to first order in perturbation theory have been done and have been reported earlier. For illustrative purposes it is useful to consider round beams for which the expressions simplify. The tune shifts, the strength of the coupling resonance and chromaticity shifts due to a single long-range beam-beam interaction where the separations are large (compared to the beam size), the beams are round and $\beta_x = \beta_y$ are given by

$$\Delta\nu_x(0,0) = \frac{N_p r_p}{2\pi\epsilon_p^N}\frac{\cos 2\theta}{d^2} \tag{1}$$

$$F_{1,-1,p} = -\frac{N_p r_p}{\pi\epsilon_p^N}\frac{\sin 2\theta}{d^2}\exp[i(\psi_x - \psi_y - (\nu_x - \nu_y - p)\frac{s}{R})] \tag{2}$$

$$\nu_x'(0,0) = 2\frac{N_p r_p}{\pi\epsilon_p^N}\frac{1}{d^3}[\cos\theta(2\cos 2\theta - 1)\tilde{\eta}_x + \sin\theta(2\cos 2\theta + 1)\tilde{\eta}_y] \tag{3}$$

Here N_p is the proton bunch intensity, r_p is the classical proton radius, ϵ_p^N is the normalized proton emittance, θ is the angle of the plane of the helix, d is the beam separation in units of the rms proton beam size, ψ_x, ψ_y are the phase advances, ν_x, ν_y are the tunes. At large distances, both the tune shift and the coupling fall as $1/d^2$ while the chromaticity falls off more rapidly as $1/d^3$. The energy dependence is contained in the scaled distance d. If there were enough separator strength to keep the physical separation between the two beams constant at different energies, then $d \propto \sqrt{E}$ and the above parameters would decrease with energy. If instead the scaled separation d is kept constant as is done during the first half of the ramp, the above parameters are independent of the energy. During the second half of the ramp d decreases due to a lack of separator strength and the parameters increase.

At 150 GeV, the tune shifts and coupling due to the beam-beam interactions are much smaller than due to the machine nonlinearities. Chromaticity and resonance strengths are however significant. At low-beta the tune shift (and spread) and resonance strengths are dominated by the contributions of the beam-beam interactions. Effects due to synchro-betatron resonances are important because of the large momentum spread in the beams and relatively large chromaticities. These resonances are individually of small width but are numerous and their overlap can transport particles to large amplitudes.

No single parameter suffices by itself to determine the impact of the beam-beam interactions. Obviously the long-range interactions are weaker at larger separations but the beam separation is limited from above by physical aperture and machine nonlinearities. In theoretically comparing two helices, the helix with the lower tune shifts, chromaticity, resonance strengths will be superior.

While the parameters shown in Equations (1) to (3) are very useful, they do not describe the transport processes that lead to particle loss or emittance growth. Ideas such as *resonance streaming* where diffusion in directions orthogonal to resonance lines are enhanced by small amounts of noise have been suggested [2], [3] as a mechanism to explain particle losses near a resonance. Quantitative calculations with dynamics in three degrees of freedom are difficult and have not been attempted. Further theoretical development of such ideas, even if they only identify the most important parameters, would clearly be very useful.

Numerical simulations offer a way to follow particle motion in fields as complex as those in the Tevatron. Dynamic aperture calculations for protons and anti-protons have been reported earlier. Lifetime calculations for anti-protons with only beam-beam fields done by colleagues at LBNL and SLAC have also been reported earlier. A simulation code (`BBSIM`) is under development at FNAL that is being used to calculate lifetime, diffusion coefficients, beam profiles and emittance growth. Unlike resonance strengths which look at individual resonances in isolation, the diffusion coefficients more nearly capture the effects of all resonances.

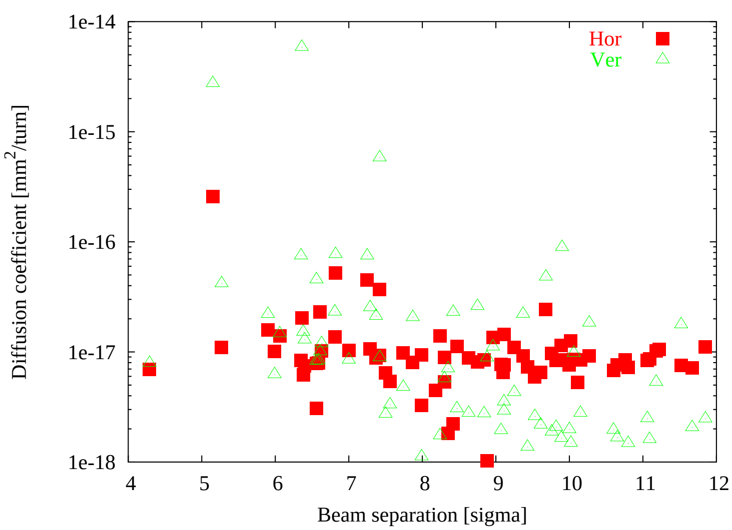

Figure 1: Horizontal and vertical diffusion coefficients at a 5σ transverse amplitude from individual parasitics at 150 GeV for anti-proton bunch 1. The horizontal axis shows the radial beam separation (in units of σ) at each parasitic.

As an example, Figure 1 shows the diffusion coefficients at 150 GeV from the individual parasitics for anti-proton bunch 1 as a function of the beam separation. We observe that two parasitics with small separations of 5.2 and 6.4 σ have the largest diffusion coefficients but the parasitic with the smallest separation has a very low diffusion coefficient. This just emphasizes the point that merely increasing the minimum separation is not enough. The diffusion in the vertical plane is on average an order of magnitude larger than in the horizontal plane. The diffusion coefficients do not however scale linearly with the number of parasitics. With all 72 parasitics included, the average diffusion coefficients are about six to seven orders of magnitude larger. This is to be expected since diffusion is very sensitive to the phase space structure created by the web of resonances. Interference of machine nonlinearities with the beam-beam fields can also change the dynamics significantly. Further development of the simulation code will include the machine nonlinearities.

3 Observations and proposed improvements

Tevatron performance in October 2002 and August 2003 before the shutdown is summarized in Table 1. We discuss these observations at each stage of the operational cycle and proposed improvements in more detail below.

	10/02	08/03	01/04	pbar/p only
Maximum Luminosity $\times 10^{30}$	36	52	52	NA
Maximum Protons/bunch at low-beta [$\times 10^9$]	170	266	235	266
Maximum Pbars/bunch at low-beta [$\times 10^9$]	19	28	30	30
Pbar loss at 150 GeV	13%	2%	2%	2%
Proton loss at 150 GeV	14%	8%	5%	5%
Pbar loss during the ramp	8%	8%	4%	2%
Proton loss during the ramp	11%	5%	5%	3%
Pbar loss during the squeeze	2%	2%	1%	0%
Proton loss during the squeeze	2%	1%	1%	0%
Pbar lifetime at start of store [hrs]	54	30	28	900
Proton lifetime at start of store [hrs]	77	29	106	300
Pbar efficiency 150 GeV $\rightarrow$ low-beta	83%	82%	93%	96%
Proton efficiency 150 GeV $\rightarrow$ low-beta	72%	83%	89%	92%

Table 1: Tevatron performance in October 2002, August 2003 and January 2004

3.1 Injection

Observations and Studies

Proton losses at injection have not been influenced much by the anti-protons. Instead the proton lifetime has largely been determined by the machine chromaticity and momentum spread. After the removal of the C0 Lambertson magnet, a significant source of impedance, protons could circulate stably in the Tevatron with lower chromaticities. The installation of a liner in the F0 Lambertson during the latest shutdown should also reduce the impedance and enable further reduction in chromaticities. Lowering the chromaticities has improved the proton lifetime at 150 GeV. The small dynamic aperture on the proton helix due to the magnet nonlinearities and restricted physical aperture at a few locations are now the main sources of beam loss.

Anti-proton losses at injection were found to be strongly influenced by beam-beam effects until recently. Experiments with only anti-protons done in September 2002 and September 2003 showed that the beam loss at 150 GeV was very small, about 2%, within the resolution error of the intensity monitors. During most of 2002 and the first half of 2003, the anti-proton losses with protons present were much larger, ranging from 10-15%. Lifetimes ranged between 1-5 hours. The anti-proton lifetime was found to depend on the anti-proton emittance, lower emittance bunches had longer lifetimes. Lifetimes at 150 GeV were not found to change much with increasing proton intensity. During the summer of 2003 several changes were made which greatly reduced the anti-proton losses from around 9% to 2%. These changes included smaller longitudinal anti-proton emittances from better coalescing in the Main Injector, lowering of chromaticity following the removal of the C0 Lambertson, lower currents in the S6 feed-down sextupole circuits which reduced strong local nonlinearities and removal of SEMs from the injection lines which reduced the emittance blow-up. Beam-beam effects at 150 GeV now have very little influence on anti-proton losses.

We briefly summarize the main conclusions from theoretical studies of beam-beam effects on the anti-protons at injection. The model of the Tevatron used for most simulations includes magnet nonlinearities based on magnet measurements made in the late 1980s. Beam-beam induced tune shifts, coupling and chromaticity were found to be small and much lower than at collision. Resonance strengths due to the beam-beam interactions were however found to be significantly larger than resonances driven by the lattice nonlinearities. Dynamic apertures calculated by simulation were found to be in good agreement with measured dynamic apertures when the Tevatron was operated at large chromaticities of (8,8) units. Furthermore the dynamic aperture was found to be relatively insensitive to the proton intensity beyond a threshold intensity. Lifetime simulations showed that the lifetime was sensitive to the chromaticity setting, in agreement with observations.

Proposed solutions

The lifetime on both helices at injection appear to be limited by physical and dynamic apertures due to the machine nonlinearities. Solutions for new helices that limit the maximum beam excursions specially in known areas of strong non-linearities and are smoother around the ring are now under active development.

3.2 Acceleration

Observations and Studies

Proton losses during acceleration have remained around 5% over the past year. Beam studies have shown that the losses occur mostly in the early part of the ramp and depend strongly on the longitudinal emittance and the quality of coalescing in the Main Injector. Short nearly Gaussian bunches have low losses, around 2%, up the ramp. There may be some influence of beam-beam interactions on proton losses but it is not significant.

Anti-proton losses during acceleration are however strongly influenced by beam-beam interactions. On average anti-proton losses are about 6% higher when protons are present. The losses are observed to well correlated with the vertical emittance, lower emittance bunches have lower losses. During the ramp the separator voltages increase linearly until about 500 GeV when the maximum voltage is reached. The beam separation, in units of the beam size, stays constant while the separator voltages are increasing but falls thereafter. As a consequence the significant portion ($\sim$ 5-6%) of anti-proton losses are observed during the second half of the ramp.

Proposed Solutions

The beam separation in the top half of the ramp can be increased by using five separators B11H, B17H, B11V, C17V and C49V instead of just the two B17H and C17V that are presently used. Helix solutions that increase the minimum separation from 3.5σ to 5σ with these separators were commissioned in August 2003.

3.3 Squeeze

Observations and Studies

Proton losses during the low-beta squeeze are usually not significant. Occasionally these losses have been large enough to quench the Tevatron. Better adjustements of the orbits and slight adjustments of tunes have usually sufficed to control losses.

Anti-proton losses were very large ($\sim$ 20-25%) until March 2002 during the step in the squeeze when the helix reverses polarity. At this stage, the minimum beam separation was less than 2σ. A helix solution was found that increased the beam separation at this point in the squeeze. That combined with a faster transition through this step reduced anti-proton losses significantly. Even with this helix the beam separation drops momentarily during the transition from the injection to the collision helix. There is some evidence of beam-beam related anti-proton losses ($\sim$ 2%) during the squeeze.

Proposed Solutions

The electrostatic separators have been conditioned to a maximum voltage of 130kV per plate but are operated at a maximum voltage of 106kV during stores. It may be possible to increase the separator voltage for the short duration when the helix reverses polarity in order to keep the beam separation constant. New helix solutions have also been proposed which require polarity switches installed on all separators. These helix solutions maintain nearly constant separations all along the squeeze and they also reduce the number of squeeze steps. The addition of the polarity switches will also allow the test of the anti-proton helix from injection to low-beta during shot set-up using protons. If the D0 Roman pots are no longer essential, then it would remove the the constraint that the anti-protons be horizontally close to these pots at top energy. In that event there would be no need to reverse the polarity for the collision helix and the injection helix could be used smoothly from injection to low-beta.

3.4 Collision

Observations and Studies

Until the end of July 2003, proton lifetimes at the start of stores were close to the values expected taking into account luminosity losses, intra-beam scattering and scattering off the residual gas. Since that time proton losses at the start of stores has increased dramatically and are typically about five times larger than the losses without anti-protons. These losses are large enough to occasionally cause quenches and significantly increase the background in the detectors. Two factors seem to be largely responsible: lower anti-proton emittances following the removal of the SEM grids and higher anti-proton intensities at low beta. Analysis of a 36(p) $\times$ 4 ($\bar{p}$) store showed that the losses were large only for those proton bunches that suffered head-on collisions but not for those bunches that experienced only long-range interactions. Analysis of bunch by bunch losses shows that typically those proton bunches that collided with the smallest vertical emittance anti-proton bunches had the largest losses. Flying wire data shows that protons have significantly larger vertical emittances than anti-protons. This suggests that losses are due to those protons which see the strongest part of the non-linear beam-beam force. Transverse offset and cogging scans to better position the colliding beams have so far not helped in reducing the losses. Lowering the chromaticity and changing tunes have helped only slightly. These losses have to be lowered, otherwise the problem will likely be exacerbated as anti-proton intensities increase.

Anti-proton lifetimes at the start of stores typically agree well with the lifetimes expected from luminosity losses and gas scattering. Emittance growth at the start of typical stores is $< 0.5\pi$mm-mrad/hr. Occasionally in some stores where proton bunch intensities are higher than 180×10^9, large emittance growth $\sim 5\pi$mm-mrad/hr is observed in most anti-proton bunches. The bunches at the head and tail of a train however have a lower emittance growth rate, so the emittance profile within a train has a scalloped shape. Emittance growth is enhanced in both planes but is larger in the vertical plane. Most often the emittance growth can be corrected by vertical tune changes of the order of 0.002. On one occasion the Tevatron electron lens was succesfully used to shift the tune of a selected bunch to correct the emittance growth.

<u>Proposed Solutions</u>

Proton Losses: The losses are likely to be lower if the beam sizes at the IPs were matched. This will require lower proton emittances all through the injector chain which may be hard to achieve in a short time. Meanwhile studies to quantify the loss process will be useful. The dependence of the losses on the tunes, chromaticity settings, relative transverse and longitudinal positions of the beams etc. need to be better quantified.

Anti-protons: The bunches at the head and tail of an anti-proton train have tunes that are different from the other bunches. The observations suggest that this occasional emittance growth is largely determined by the tune. One way to ensure that the tunes do not wander to undesirable values is to continuously monitor the anti-proton tune - as can be done for example by the tune fitter under development using the directional pick-up in the 1.7 GHz Schottky monitor.

The parasitics nearest to the IPs occur at the smallest separations and are also locations of large β values. This suggests that limitations due to the parasitics, specially at higher proton intensities, could be mitigated by increasing the separations at these nearest parasitics. New helix solutions with short separators installed in place of the Q1 low-beta quadrupoles at CDF and the Roman pots at D0 have been examined. These four additional separators, each about 1.0 m long, can increase the beam separation around the ring by about 17% and at the nearest parasitics by about 14% [4]. If studies show that beam losses can be reduced by increasing the separations, then these additional separators would be helpful.

4 Measurements and Diagnostics

<u>Orbit measurements with coalesced beams</u>

At present anti-proton orbits cannot be measured at all with the BPMs in regular stores. An upgrade of the BPM system is planned which will (a) improve the orbit measurement resolution to 20 microns from the present 200 microns, (b) be able to measure positions of coalesced bunches more accurately than at present, (c) be able to measure anti-proton orbits when desired during regular stores with protons present. If the orbits can be measured at 150 GeV, the ramp and 980 GeV, then the helix can be better controlled to maintain the required beam separation. This is specially important since the orbits are known to change in time even without any externally applied changes. If the orbits are well controlled, then better control of basic parameters such as tunes, coupling and chromaticity on the helices would be possible. If turn by turn orbits of the anti-protons are available from multiple BPMs, then nonlinear effects due to the beam-beam effects can also be measured.

Bunch by bunch measurements of tune and chromaticity

Early attempts to measure the tunes of anti-proton bunches at low-beta used a gated noise signal to excite selected bunches and the coherent response was measured. More recently attempts have been made with the new 1.7GHz Schottky detector to measure the tunes and chromaticities of individual anti-proton bunches. These attempts have not led to reproducible values and therefore comparison with theoretical predictions have not been meaningful. This comparison is an important test of the beam-beam model. The sources of errors in these measurements need to be understood and corrected. Phenomena such as tune dependent emittance growth ("scallops") could then be understood and corrected.

Automated tune and chromaticity measurement

This technique under development automates the measurement of the tune from the Schottky spectrum so the tune can be followed over time. The analysis to extract chromaticity and other information from the synchrotron sidebands in the spectrum needs to be incorporated into the measurement. Once available, this tool can be used to observe changes in tune and chromaticity due to beam-beam effects and correlated with beam losses, emittance growth and backgrounds in the detectors.

Detuning with amplitude and resonance driving terms

These are the important nonlinear characteristics of the beam-beam force. They can be measured by kicking the beam and Fourier analyzing the turn by turn data from the BPMs. The measured detuning and resonance driving terms can be compared with theoretical predictions and will be important checks of the beam-beam model. Variations of the resonance driving terms along the ring are a useful diagnostic to locate strong local nonlinearities [5].

Emittance measurements

The dependence of beam-beam related losses on the emittance of the beams is not well quantified. Emittance measurements at 150 GeV and the ramp need to be more reliable in order to increase our understanding. Improvement of the flying wire measurements should continue with high priority. Emittances reported by the flying wires and the synchrotron light monitor should be well calibrated against each other. The high proton losses observed at the beginning of stores is related to the emittance mismatch between the beams. Reliable emittance measurements will help to understand this phenomenon better and control the losses.

5 Beam studies

Understanding proton losses at the start of stores

These losses are now limiting the integrated luminosity delivered. To understand how well the beam sizes need to be matched at the IPs, it would help to quantify the dependence of the losses on the mismatch. For example, the proton beam could be scraped in the Tevatron and losses as a function of proton beam size could be measured. This would determine if there is a sharp onset or a gradual increase in losses as the mismatch increases. There may also be some influence of the low-beta quadrupoles. The losses could be studied at higher β^* while keeping $\beta_x^* = \beta_y^*$. The head-on beam-beam tune spreads would be the same but the influence of the low-beta quadrupoles would be weaker.

Operation with different numbers of bunches e.g. 18×18

The impact of the long-range interactions can be reduced by having fewer bunches. For example with 18×18 bunches (bunch spacing of 42 buckets), the luminosity can be preserved if the anti-proton bunch intensity is doubled. The drawback is the doubling of the interactions per bunch crossing in the detectors. It is estimated that this limit will not be reached until the luminosity is close to $2\times10^{32}\text{sec}^{-2}\text{cm}^{-1}$ - about four times present luminosities. The DOE review in July 2003 also recommended exploration of alternative bunch configurations.

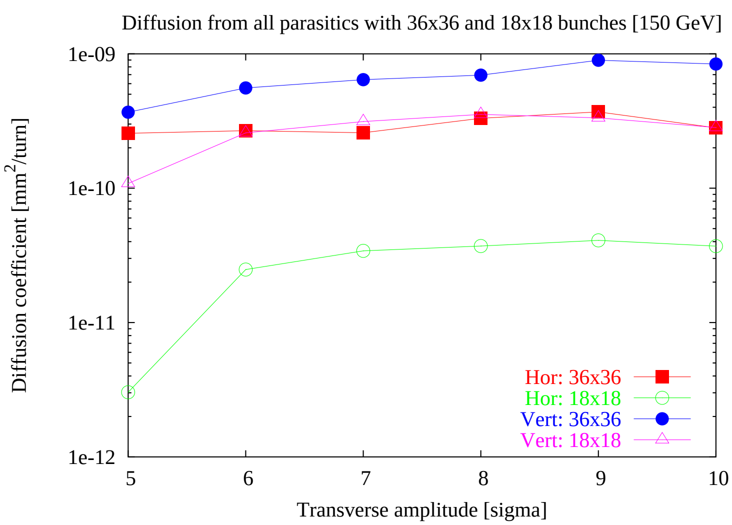

Figure 2: Horizontal and vertical diffusion coefficients with 36×36 bunches and 18×18 bunches from all the long-range interactions at 150 GeV for anti-proton bunch 1. The transverse amplitude (units of sigma) is plotted on the horizontal axis.

Theoretical studies of resonance strengths and diffusion coefficients predict that the anti-proton lifetime will be better with 18×18 bunches. Figure 2 compares the diffusion coefficients in the two planes with 36×36 and 18×18 bunches. The horizontal diffusion is about an order of magnitude lower while the vertical diffusion is about a factor of two lower with 18×18 bunches. Initial lifetime calculations also show larger lifetimes with 18×18 bunches. This (or a similar configuration) needs to be tested with machine studies. Initial studies could be done with 18 proton bunches colliding with 4 anti-proton bunches at present intensities. If these studies show lower losses then a plan that would allow injecting anti-protons with twice the present intensities needs to be developed. The important question in the Tevatron will be to determine the impact of the larger longitudinal emittance of these anti-proton bunches on losses.

Importance of the nearest parasitics at collision

Theoretical studies suggest that the parasitics nearest the IPs have a strong influence on the anti-proton dynamics at collision but the experimental studies to date have not confirmed this. This is important to know since it will determine whether additional separators are needed close to the IRs. One suggested study [6] is to inject fewer than twelve proton bunches in a train and collide the train with a regular bunch of twelve anti-proton bunches. The lifetimes of anti-proton bunches which experience both nearest parasitics could be compared with those that experience neither. Another possibility is to introduce a small ($< 50\mu$rad) crossing angle which increases only the separation at the nearest parasitics but leaves the orbits elsewhere unchanged.

Studies with only protons or anti-protons

To optimize the anti-proton helix, most studies can be done with protons placed on the anti-proton helix. Losses and lifetimes would be measured from 150GeV through the ramp to the last stage of the injection helix during the squeeze. When there is an adequate supply of anti-protons, these studies can be repeated with only anti-protons but proceeding to the final step of the squeeze. These will help better quantify the losses due to the beam-beam interaction at all stages. Dependence of losses on important parameters such as emittance and chromaticity would be studied.

6 Beam-beam compensation

Tevatron Electron Lens (TEL)

The TEL has been in operation since March 2001 and aims to compensate the tune spread between bunches at top energy. The electron gun was replaced in Janurary 2003 by another gun which creates a smoother Gaussian profile of the electron beam. In studies with the electron lens acting on protons, the smoother field was found to preserve the lifetime of the protons and was a significant improvement over the previous gun which created a more rectangular profile. The alignment of the lens is very critical - for example the sign of the induced tune shift can change due to small changes in the orbit. In a beam study performed in a store where scallops had developed, the electron lens was successfully used to change the tuneshift of a selected anti-proton bunch and thereby reduce its emittance growth rate. The electron lens is also routinely used to remove coasting protons circulating in the ring by resonant excitation of particles in the abort gaps. It has also been used on occasion to tickle a bunch to increase the signal to noise raio for a tune measurement. Further work on the electron lens to make it an operational device for tune shift compensation is continuing. The improvements required include better control of the electron lens orbit, improved stabilization of electron currents and perhaps a wider electron beam.

Wire Compensation

Compensation of the long-range interactions by steady current carrying wires is also under investigation for the Tevatron following a similar proposal for the LHC. A preliminary investigation (reviewed in October 2003) with four 1m long wires placed in four warm straight sections showed that the dynamic aperture of a selected anti-proton bunch at 150 GeV could be significantly increased by appropriate placement of the wires and carefully selected currents. Several other features must be demonstrated before the scheme can progress to a practical test. Robustness of the compensation with respect to achievable alignment tolerances and current stability must be shown. It is also clear that multiple wires will be required at each location to track the changes in the helix from injection to collision. The impact of the wires on the protons needs to be studied. If the compensation is required only at top energy and for a few selected parasitics such as those nearest to the IPs, the compensation would be simpler and easier to implement. Nevertheless the full potential of the wire compensation scheme and how it can complement the TEL needs to be investigated. Table 2 shows the different stages of the Tevatron and different phenomena which could be examined.

This study is continuing in collaboration with CERN colleagues, J.P. Koutchouk and F. Zimmermann. The plan includes collaboration on wire experiments scheduled at the SPS which will allow us to validate the theoretical tools developed here. The next report on the wire compensation studies will be delivered at the beginning of April 2004. The decision on whether to proceed with building a wire compensation prototype will be made following the report.

Stage	Problem	Compensation strategy
INJECTION	$\bar{p}$ losses $\sim 2\%$	No need of compensation
	$\bar{p}$ losses $>\sim 5\%$	Wires could be helpful
	Strong-strong effects	Changes in tunes, tune splits,... Active compensation methods would need study
RAMP	$\bar{p}$ losses $> 5\%$ and/or large emittance change	Best with stronger separators after 500 GeV. Perhaps wires can complement
COGGING & SQUEEZE	$\bar{p}$ losses $> 5\%$	Changes in helix
COLLISION	Bad lifetime or emittance growth from isolated parasitics	Wires most likely to be helpful
	Large emittance growth of a few bunches	TEL best suited
	Strong-strong effects from head-on collisions	Other means - larger tune splits, larger tune spreads etc.
	Strong-strong effects from parasitics	Needs study

Table 2: Different stages of the Tevatron and possible compensation strategies.

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